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Remote Labolatory with Modular Inertial Measuring Unit Platform

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Abstract

The document describes the usage of an inertial measurement unit platform in a remote laboratory. The platform is based on widely used modern MEMS components, such as accelerometers and gyroscopes, in combination with digital signal processing and web technologies. Students can work on the real device from anywhere in the world. They can measure data from a real process remotely and subsequently train various signal processing techniques using this data. They can also get familiar with the properties and drawbacks of the inertial sensors used on the remotely controlled device.

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Keywords: Remote laboratory; Teaching aids; Inertial Measuring Unit; MEMS sensors, Sensor fusion

1. Introduction

MEMS (Microelectromechanical systems) sensors are components which are widely used to determine the position of an object in an inertial frame of reference. Their signals can be used quite straightforwardly in some applications. In other applications (for example in small UAVs, mobile robots) more sophisticated methods have to be used to process signals from these sensors.

Inertial measurement units (IMUs) measure inertial state variables of an object in 3D space, such as gravitational forces, orientation and velocity [10]. The objects containing such units can be robots, airplanes, satellites etc. IMUs are equipped with accelerometers and gyroscopes. Their MEMS versions have been available on the market for

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several years. Nowadays, they can be used widely thanks to their size and low price and mass production.

Accelerometers and gyroscopes have some disadvantages [10]. A way to compensate them is to combine more sensors with different properties in order to achieve better general performance.

[5] shows several ways of sensor data fusion like com-plementary or Kalman filter.

Since workshops on service robotics at our faculty are practically oriented and we prefer students to work with real devices a modular IMU platform equipped with accelerometers and gyroscopes was created. A MATLAB Simulink [2, 4] block representing this measurement unit working in real time was also prepared. With this equipment students can evaluate sensor properties and process their signals in an environment known to them.

2. Electronic Board

To make the teaching process more practical and interesting to students [15], a hardware for IMU was prepared. The purpose of the mechanical part described in the next section is to allow some movement of the moving part while keeping the whole construction in the same place. We can measure the position of the object changed by movement, and obtain the position using a different reference method. The results of signal processing can be compared to these reference measurements. The goal of this approach is to let students use the sensors, try and evaluate several digital processing techniques, compare their results and choose the most appropriate one of these techniques.

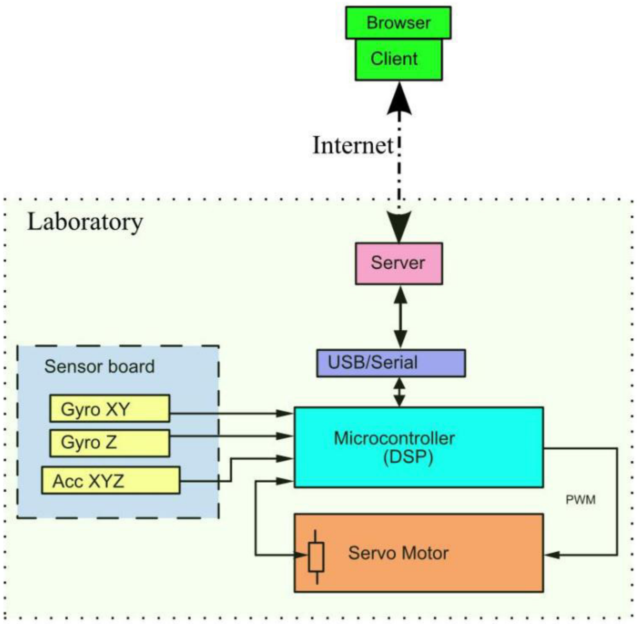

Fig. 1. Block diagram of the electronic part of the platform and its connection to the user

The most important part of the platform is the electronics. Its block diagram is shown in Fig. 1. There are two electronic boards. One of these boards is a control board with a digital signal controller used to convert signals from the sensors to digital data and to make some basic data processing. A 16 bit digital signal controller of the type dsPIC33FJ64GP306A [3] by Microchip is used. A PICKIT3 programmer was used to debug and program it via ICSP interface.

The other board is a sensor board. The approach with separate boards allows the user to change the sensor board and use various types of sensors.

Our sensor board is equipped with an MMA7361 [14] which is a 3-axis accelerometer with an analog output by Freescale. It also contains two gyroscopes, LPY530AL [12] measuring angular rate around axes X and Y and LPR530AL [11] measuring around the Z axis. Both types are manufactured by STMicroelectronics.

The controller generates a standard PWM (Pulse Width Modulation) signal of 50Hz frequency and nominal impulse duration of 1.5ms. This signal controls a HexTronik HXT900 servo motor. Its purpose is to move the sensor board. Sensor board inertial variables can be measured with the sensor board.

In order to have a more precise position signal, the servo motor has been modified. After disassembling, the internal position feedback voltage was lead out from the potentiometer and was connected to the controller. This signal is assumed to be the reference signal for measurements of the MEMS inertial sensors.

A serial port and a USB/Serial port adapter are used to connect the controller to the computer. In our case, the computer is the server providing the remote access of the laboratory.

The users can access the system remotely via a client site running in their browser.

3. Mechanical design

Fig. 2 shows a sketch of the mechanical design. There is a vertical wall with a protractor drawn on it. A servo motor in position mode is mounted in the middle of the protractor and its shaft is oriented horizontally. A deck with the electronic boards is located on the shaft.

There is an arrow pointing at the protractor in the direction of the board plane. The indicated angle is the angle between the horizontal plane and the plane of the board and it can be measured visually using the protractor. A photograph of the platform is shown in Fig. 10. The angle changes when the motor is moved. This angle and the angular rate should also be measured by an appropriate signal processing of the output of the sensor board (gravity projection and gyroscopic moment).

An additional arm can be mounted on the shaft. Subsequently, the sensor will be located further from the center of rotation and the output of the accelerometers on the board will be affected by centrifugal and tangential acceleration. In this case, a stronger servo motor should be considered.

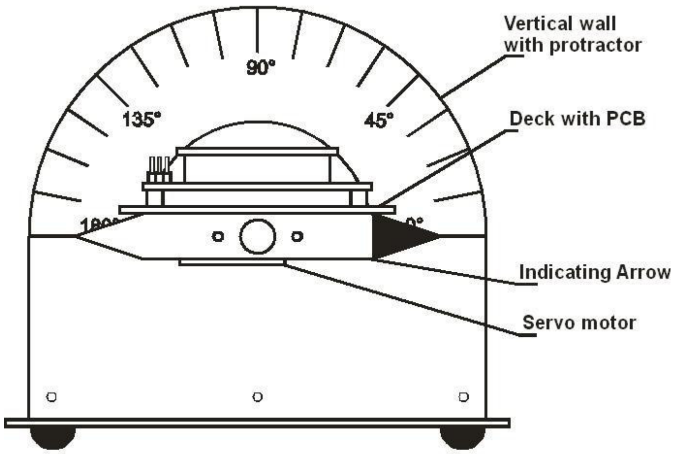

Fig. 2. Mechanical construction of the stand

4. Communication protocol

The used controller was programmed in C language. MPLAB IDE was used for programming and debugging. Its firmware uses an internal analog to digital converter to measure the signal from a sensor and also to generate the required PWM signal for the motor.

The controller uses a serial port to communicate with the PC set according to Table 1.

Table 1 Serial port settings

Parameter	Value
Data bits	8
Communication speed	115200 baud
Flow control	None
Parity	No
Stopbits	1

The PC sends commands to the IMU in a vector form which consists of three ASCII values (the first value represents tens, the second value represents units and the third is delimiter carriage return character).

The IMU device sends data in text form. Lines of the following format are used:

- Time [ms]
- Angle from potentiometer [degree]
- Acceleration from accelerometer X[ms^{-2}]
- Acceleration from accelerometer Y [ms^{-2}]
- Acceleration from accelerometer Z [ms^{-2}]
- Angular rate from gyroscope around X axis [$rads^{-1}$]
- Angular rate from gyroscope around Y axis [rad^{-1}]
- Angular rate from gyroscope around Z axis [$rads^{-1}$]

The items are Tab-separated and the lines are separated by a carriage return character. Note that not all variables are affected by the movement of the motor. In an ideal case some of them stay constant.

Highly motivated students are allowed to modify the firmware and protocol with their own ideas or special requirements.

5. Sensor fusion algorithms

Properties of MEMS *sensors*

In order to use sensor data fusion correctly, the properties of the sensors have to be known. MEMS accelerometers are good for static measurements like slow inclinometers in cell phones.

On the other hand, their output contains high frequency noise and they detect not only gravitational but also centrifugal and linear acceleration, which causes disturbances in inertial measurements. MEMS gyroscopes measure angular rate and their output has to be integrated to obtain the angle. Hence they act very well at higher frequencies. The integration of angular rate also means integration of little deviations. Subsequently it causes significant drift of angle values.

Complementary filter

The complementary filter explained in [1] is one of the most convenient ways of sensor data fusion in case of disturbances. It is based on complementary spectral characteristics of the noise. Let us assume signal x and two of its measurements y_1 and y_2 with high frequency noise μ_1 and low frequency disturbance μ_2.

$$y_1 = x + \mu_1 \quad (1)$$

$$y_2 = x + \mu_2$$

We can assume a complementary filter composed of two transfer functions with complementary spectral characteristics $F_1(s)$ and $F_2(s)$, where $F1(s)$ is a low pass filter transfer function and $F_2(s)$ is a high pass filter transfer function.

$$F_1(s) + F_2(s) = 1 \quad (2)$$

Consequently these filters pass the whole frequency range of the input signal. However, $F_1(s)$ suppresses the noise μ_1 and $F_2(s)$ is designed to reduce the slow disturbance μ_2. The previous statement can be described by following equation:

$$\hat{X}(s) = F_1(s) * Y_1(s) + F_2(s) * Y_1(s) = \quad (3)$$

$$X(s) + F_1(s) * \mu_1(s) + F_2(s) * \mu_2(s) =$$

The block diagram of a complementary filter used by students is shown in Fig. 3

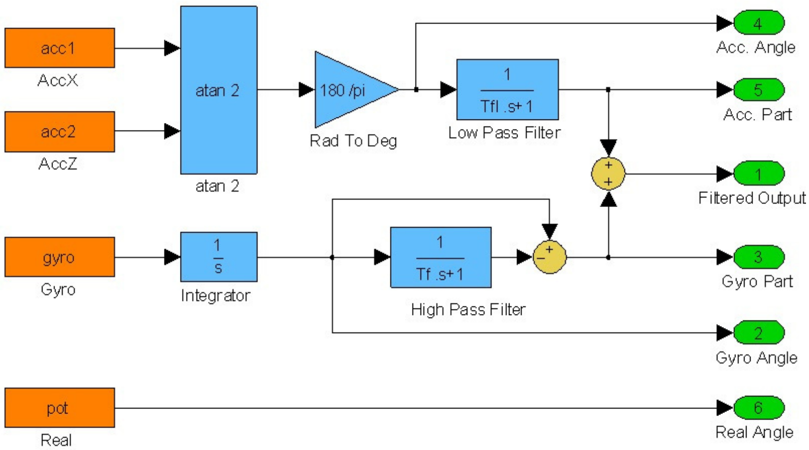

Fig. 3. Block diagram of complementary filter

Kalman filter

The Kalman filter is a widely used state estimator. It takes into account the model of the controlled system. Unlike the classical approaches, it also reckons with the properties of the measurement (noise and other disturbances). The Kalman filter requires the state space model of the system and is usually applied to the discrete version of the system.

The principle of the Kalman filter is more difficult to understand than the complementary filter. It is more computationally complex (matrix inversion, transposition and multiplication) which used to be a problem. Nowadays, the Kalman filter can be easily implemented in modern digital signal controllers.

Because of the complexity, the fact that the students are not too experienced and the workshops are also hardware oriented we pay much more attention on complementary filter that is easier to learn. However, the Kalman filter is a good topic for thesis and more advanced student projects.

More information on the Kalman filter can be found in [6]. We would like to motivate the students to work with this method.

6. System configuration of the server

Since the requirements for the server are not very high, we used a regular PC with the following configuration:

- CPU: AMD Turion 64 X2 Mobile TL-60 (Trinidad)
- RAM: 2 x 2048 Mbytes DDR2 PC2-5300 Kingston CL5 Dual Channel
- MB: Quanta 30D0 nForce 520
- VGA: G86M GeForce 8400M GS 128 MB
- HDD: FUJITSU MHW2120BH USB Device, USB 2.0 EXT 17GB

The server is equipped with a camera (USB Video Device Logitech C170).
We used Ubuntu 12.10 with Geany 1.22, VLC media player 2.0.4 Twoflower and XAMPP for Linux 1.8.1

7. Online access

The server application is located on server at our faculty. If the device is busy, the server refuses access to the hardware for new users.

Otherwise a user can connect to the server with a username and password. After logging in (Fig. 4), the camera view of the device is shown on the left side of the screen (Fig. 5).

There are two array fields situated on the right side of the screen. The first represents angles. These angles are entered as a vector of values in degrees. The second field is meant for the time vector. If these two vectors do not have the same length, an error is displayed. Otherwise, the device will start after pushing the “Go” button. Users can see the working device online on the camera screen.

The system returns vectors with length determined by the duration of the process. The duration is defined as time vector increased by 5 seconds so the system can also record the transition response.

After data acquisition a message reading "download data file" is displayed to the user. Users can choose the filename *but the extension is always *.dat.*

Students can be easily imported this file into Matlab, Octave, Excel or other similar software depending on their preferences.

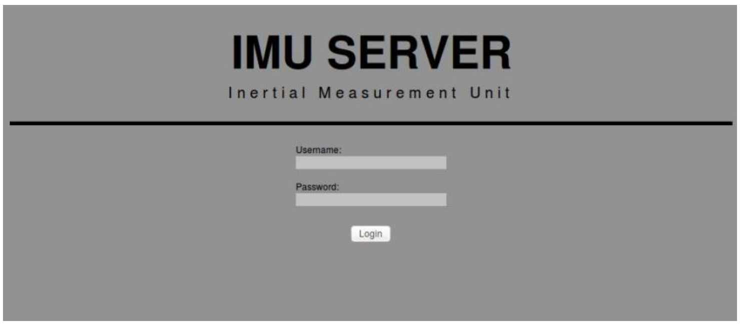

Fig. 4. Login to the remote application

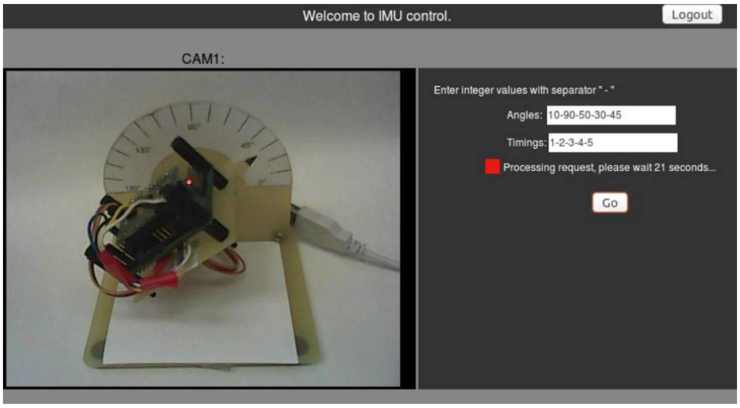

Fig. 5. Screen with live camera view and data input area

8. Data import and processing

To import data from the exported file into Matlab or Octave we use the "load mydata.dat" command. A variable called "*mydata*" containing eight vectors appears in the workspace. These vectors can be accessed by standard Matlab commands.

The first column represents time ("*Time* = *mydata*(:,1);") and the second the potentiometer value ("*pot* = *mydata*(:,2);"). The third, fourth and fifth columns are the accelerometer values ("*acc* = *mydata*(:,3:5);") and the sixth, seventh and eighth are the gyroscope values ("*gyro*= *mydata*(:,5:8);").

The data can be also processed using a Matlab script (m-file) or the Matlab-Simulink block "from workspace" by selecting the appropriate vector.

9. Measurement example

To demonstrate the functionality of the laboratory we performed the following experiment. We logged in on the server and set the board to the horizontal position (angle of 0 degrees).

After initializing the platform a step of 90 degrees was applied and the motor moved the boards to the vertical position.

Fig. 6a shows the signal from the internal potentiometer of the servo motor (real angle) and the angle gained from the accelerometer without any filtering. Note the significant oscillation of the response and noise present in the signal. The signal also displays overshooting.

Fig. 6b shows the comparison of the real angle and the angle gained from the gyroscope. The signals correspond to each other in transient states but the steady state value of the gyroscope rises in time. Such a signal cannot be used directly to measure the angle. Hence this sensor is better at higher frequencies.

Signals from the accelerometer and gyroscopes are filtered and the result is shown in Fig. 7a. Their sum is compared to the real angle in Fig. 7b.

IMU devices offer to students various views of the signal processing. The IMU platform is a very useful tool to gain work experience with raw signal data and signal noise reduction. Students can see that the raw signal from the device needs to be filtered. They can implement various techniques, such as the complementary filter or the Kalman filter, to deal with this problem.

The main contribution of the laboratory is to allow students to work with this system from a remote location without having to attend a workshop at the university. This allows us to manage the time distribution of the laboratory equipment more efficiently.

Remote access is only one of the ways how we can utilize the described hardware platform.

Additionally, there is a possibility to change the sensor board to compare the behavior of various sensors.

Students can even modify the program used in the digital signal processor and implement the data fusion algorithms directly in it. This requires, of course, additional knowledge of the C programming language and the DSP programming.

We also integrated this platform into the Matlab Simulink environment. The whole system is represented by a single Simulink block. Its input is a desired angle and its output provides the measured data.

Users can easily design advanced methods of filtering using basic Simulink blocks.

a b

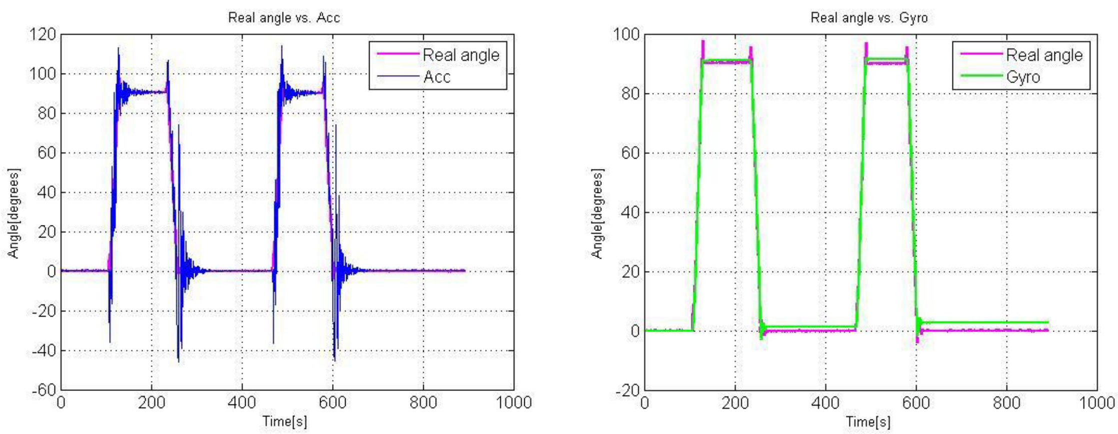

Fig. 6. (a)Comparison of the angle obtained from accelerometer and the real angle read from the potentiometer, (b) Comparison of the angle obtained from gyroscope and the real angle read from the potentiometer

a b

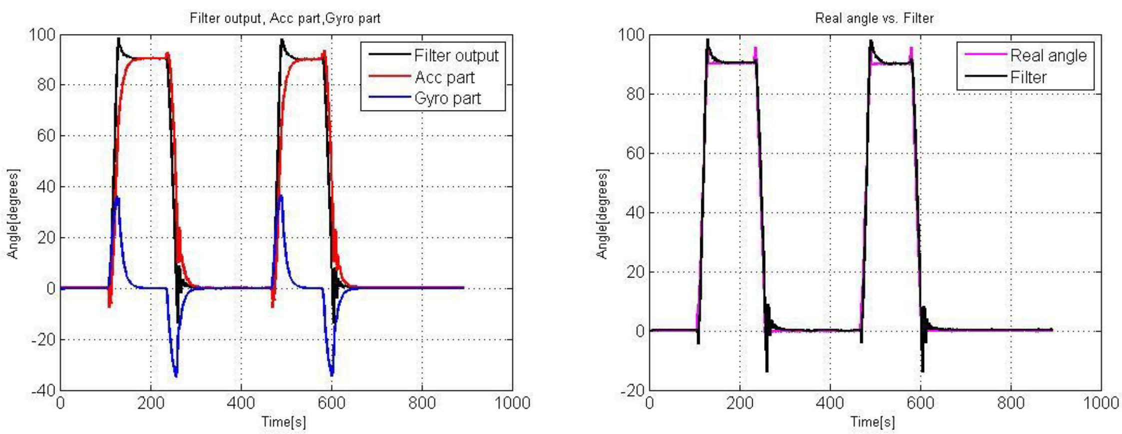

Fig. 7. (a) Filtered signal from the accelerometer and gyroscope and their sum (b) Comparison of the complementary filter output and the real value from potentiometer

10. CONCLUSION

The IMU platform is designed to support the education of various workshops of study programs at our faculty, especially in Applied informatics, Industrial informatics and Robotics.

It can be programmed directly, used with Matlab Simulink or accessed remotely via web interface. The described communication protocol allows students to work with various programming languages, such as Java, C/C++ and Matlab, to implement their own filtering algorithms, robot inertial navigation systems or other automation techniques.

In order to understand feedback control theory, it is essential that students learn to obtain signals and filter noise from sensors used in real industrial applications, robotic platforms or smartphones. Students will be able to design their own solutions to acquire sensor signals and to control the angle of the servo motor shaft. In the future, we will continue to work on a virtual and remote laboratory to improve the education by using contemporary sensors in the field of robotics at our faculty.

The goal of this paper was to introduce the possibility of remote access to the platform. This concept provides new possibilities for students with limited access to the workshops or our laboratories.

The remote access has some limitations, for example, the users cannot modify the hardware configuration.

We plan to add more languages to the user interface and extend the functionality by a possibility to configure the DSP remotely.

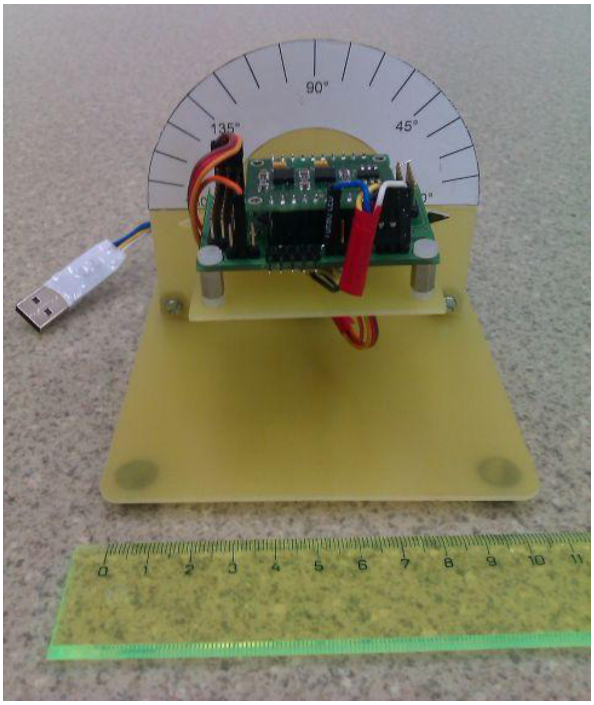

Fig. 8. Photograph of the platform

11. Acknowledgments

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